

## **SECTION II**

### **FUEL CELLS FOR ELECTRIC VEHICLE PROPULSION**

Section II explains the principle of fuel cell operation and the practical considerations for their application to power electric vehicles, the main fuel cell types developed to date, and the reasons why the proton exchange membrane (PEM) technology is the leading candidate and current focus for automotive applications of fuel cells. The fuel cell subsystems needed to meet the functional requirements for automotive applications are introduced, and the most important PEM fuel cell component and balance-of-plant technologies are discussed. This introduction is followed by a brief discussion of the main issues surrounding the development of complete fuel cell electric engines. Finally, some considerations pertaining to fuel cell efficiency and emissions are presented. The discussions are intended to provide context for the subsequent review of the Panels findings and conclusions.

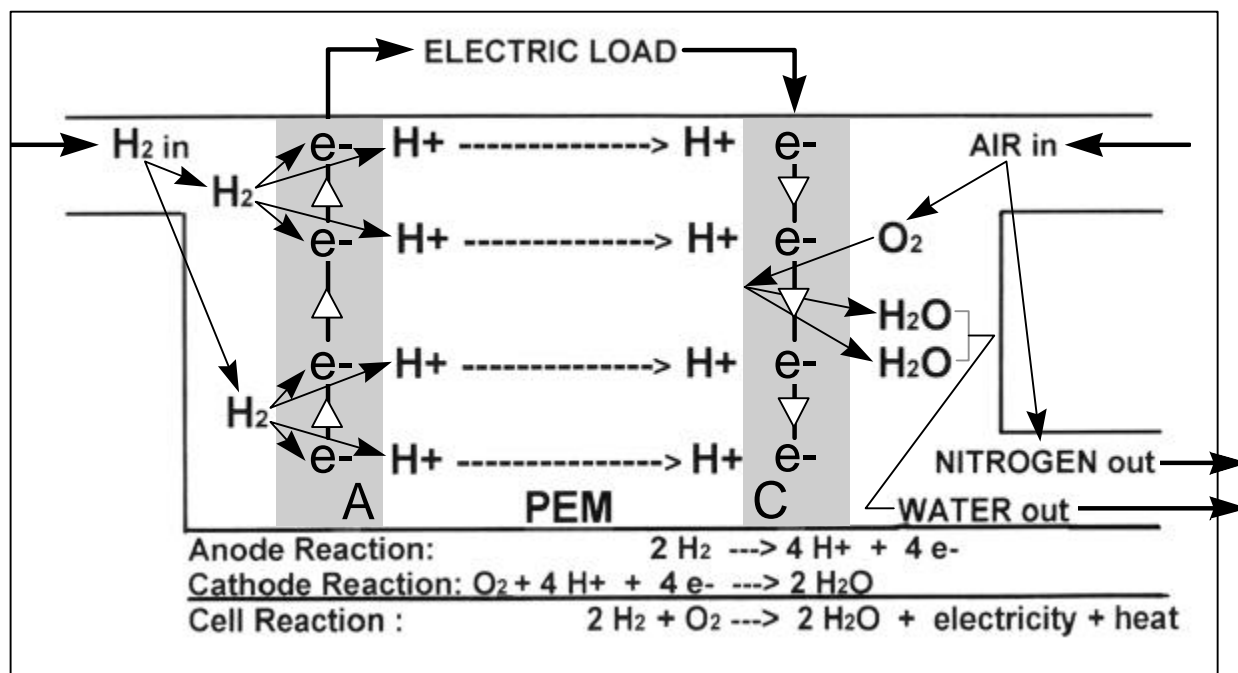
#### **II.1 PRINCIPLE FEATURES AND PRACTICAL REQUIREMENTS**

The operating principle of a hydrogen-oxygen fuel cell — the originally discovered and simplest embodiment of the fuel cell concept — is illustrated in Figure II-1.

Hydrogen gas is fed to one electrode which is coated with a metal such as platinum that catalyzes the dissociation of hydrogen molecules into atoms and the ionization of these atoms into hydrogen ions ( $H^+$ , or protons). This catalytic “hydrogen electrode” also is in contact with an “electrolyte”, water or other liquids in which polar molecules will ionize and, as a result, are able to conduct electricity.<sup>1</sup>

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<sup>1</sup> As explained in the next section, fuel cells can be made to work with a number of different electrolytes, both aqueous and nonaqueous. Although details of the electrochemical processes at the electrodes and in the electrolyte depend on the specific electrolyte used, the basic principles governing fuel cell operation are the same.



**Figure II-1. Principle of a Hydrogen-Air Fuel Cell**

Protons leave the hydrogen electrode and enter the electrolyte, leaving behind electrons which give the hydrogen electrode a negative charge and polarity. At the other electrode, oxygen is dissociated and ionized by accepting electrons from the electrode and reacting with water. Negatively charged hydroxyl ions ( $OH^-$ ) enter the electrolyte, leaving the oxygen electrode positively charged. In the electrolyte, protons ( $H^+$ ) and hydroxyl ions ( $OH^-$ ) combine to form water ( $H_2O$ ).

If an external electric load is connected between the negative hydrogen electrode and the positive oxygen electrode, an electric current will flow between these electrodes through the load as long as the flows of hydrogen and oxygen continue. The flow of current through a load is the electric power derived from converting the chemical energy of the hydrogen-oxygen reactant pair directly to electricity. Since no combustion is involved, the only chemical product from the operation of a hydrogen-oxygen fuel cell is water.

If a fuel cell is operated at very low conversion rates (currents and power), nearly the full chemical energy of the hydrogen-oxygen reactant pair can be converted into electricity. At higher rates, fuel cell voltage (and thus efficiency) is reduced by losses due to the electric resistance of cells (IR loss), the slow transport of gases to the reaction sites at the electrode-electrolyte interfaces, and/or the low reaction rates at the electrodes.

The invention more than 60 years ago of porous electrodes with large, catalytically active surface areas and correspondingly large interfaces with the electrolyte was an important step toward attaining high levels of power for a given volume (power density) of fuel cells while retaining good efficiencies. Such “gas diffusion” electrodes permit rapid transport of gases to, and their electrochemical reaction at fuel cell electrodes. With the use of properly designed gas diffusion electrodes, hydrogen-oxygen fuel cells can be 50-65% efficient in practice, far higher than what is typical for internal combustion engines. A key advance on the way to hydrogen-oxygen and other types of fuel cell technologies was to assemble a number of individual fuel cells mechanically and electrically in series into compact “stacks” with practical levels of voltage, as explained in the next section.

As will be discussed in this report (see Section III.2.A), neither hydrogen nor pure oxygen are feasible choices for general vehicle propulsion in view of their high cost and because of the technical difficulties and high costs to store practical quantities of these gases on vehicles. Like combustion-based automobile engines, automotive fuel cells therefore must use ambient air as the source of the required oxygen, and they must be able to operate on widely available hydrocarbon fuels such as gasoline and other petroleum products which are easily stored onboard vehicles<sup>2</sup>. Methanol, an alcohol, also is being considered seriously for future fuel cell vehicles.

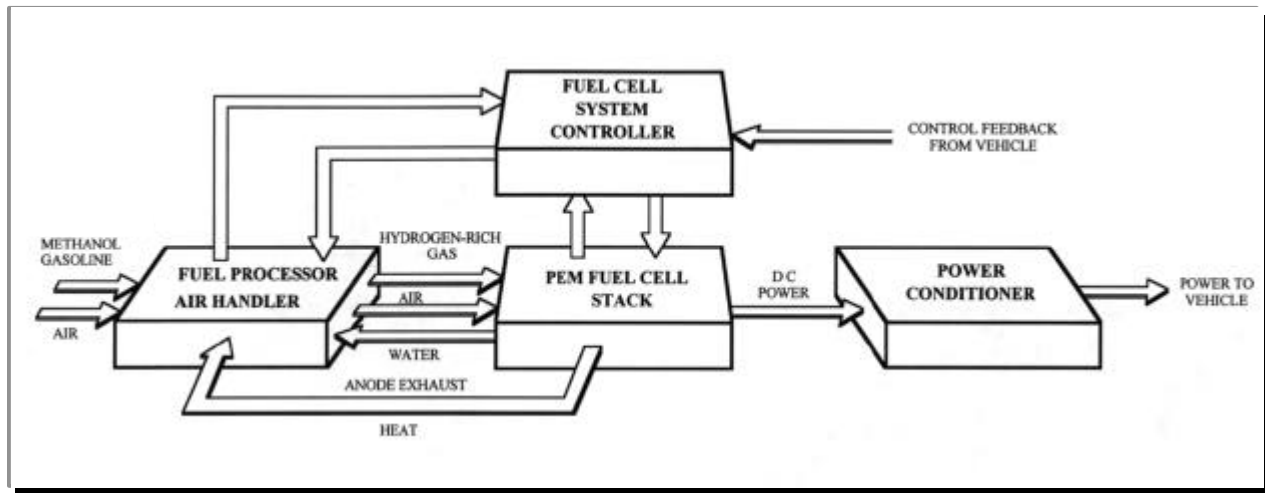
Ambient air can be used with little or no pretreatment as the source of oxygen for several fuel cell types including those that use PEM electrolytes. Unfortunately, however, hydrocarbons and alcohols have impractically low electrochemical reactivity, especially at the temperatures considered practical for automotive applications. If these fuels are to be used in fuel cells, they must first be converted to a hydrogen-rich gas in catalytic-chemical reactors. Such “fuel processors” add to the weight, volume and cost of the fuel cell power plant. They also reduce fuel cell system efficiency, and their operation can result in some albeit generally very low emissions. The development of compact, clean and inexpensive processors for the different fuels under consideration, and the efficient operation of such processors in combination with the fuel cell are among the most difficult tasks in the development of automotive fuel cell power plants.

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<sup>2</sup> Natural gas, the least expensive hydrocarbon fuel, is an excellent choice for stationary fuel cells that generate electric power. However, natural gas is not presently being considered by the developers of automotive fuel cell technology because car makers have a strong preference for storing only unpressurized, liquid fuels on personal automobiles.

Finally, fuel cell stacks, fuel processors, auxiliary equipment (e.g., for pressurization and humidification of gases) and the required sensors and controls need to be integrated mechanically, thermally, chemically and electrically into compact, fully functional and potentially low cost fuel cell power plants. Achieving this integration while preserving the potential of fuel cells for high efficiency and near-zero emissions is the ultimate challenge in the development of fuel cell electric engines for automobiles.

The main subsystems of a hydrocarbon-air fuel cell power plant and their functional integration are shown schematically in Figure II-2 and discussed in the next several sections.



**Figure II-2. Schematic of Fuel Cell Power Plant/Electric Engine**

Figure II-2 also shows the power conditioner, a power electronic device that converts and controls the direct-current output of the fuel cell power plant and serves as its interface with the electric motor. Power conditioners are excluded from this study because their technology has been brought to the level of commercial readiness during the last few years as part of developing battery-powered electric vehicle technology. The remaining issue with electric vehicle power conditioners — their relatively high cost — is likely to be resolved if and when fuel cell and/or battery power conditioners are produced in the numbers required for mass-produced electric vehicles.

## II.2 FUEL CELL TECHNOLOGY

### A. TYPES OF FUEL CELLS

Over the past three decades, several different types of fuel cells have been developed for space and terrestrial power generation applications. Because the electrolyte is the technical feature that determines many of the key characteristics, these fuel cells are usually categorized by electrolyte. Table II-1 summarizes the main types and their characteristics.

**Table II-1. Characteristics of Various Types of Fuel Cells**

Fuel Cell Type	Type of Electrolyte	Operating Temp. (°C)	Current Density	Need for Fuel Processor	Compatibility with CO <sub>2</sub>	Stage of Development	Current Prospects For	
							High Efficiency	Low Cost
PEMFC	Proton Exchange Membrane	70-80	High	Yes	Yes	Early prototypes	Good	Good
AFC	Aqueous Alkaline	80-100	High	Yes	No	Space application	Good	Good
PAFC	Phosphoric Acid	200-220	Moderate	Yes	Yes	Early commercial applications	Good	Fair
MCFC	Molten Carbonate	600-650	Moderate	Yes <sup>a</sup>	Yes	Field demonstrations	Good	Fair
SOFC	Solid-Oxide	800-1000	High	Yes <sup>a</sup>	Yes	Laboratory demonstrations	Good	Fair-good
DMFC	Proton Exchange Membrane	70-80	Moderate	No	Yes	Research	Poor	Poor-fair

<sup>a</sup>Except for natural gas fuel

When considering applicability of fuel cells for automobile propulsion, one important factor is operating temperature. The time and energy needed to bring the high temperature molten carbonate (MCFC)

and solid oxide (SOFC) fuel cells to operating temperature, and the volume and cost of the high-performance thermal insulation that would be required to maintain high operating temperatures at all times, almost certainly rule out these fuel cell types for propulsion of cars, although perhaps not for transportation applications (such as locomotives) that require large power plants and involve near-continuous use. Besides near-ambient temperatures, fuel cells for automobile propulsion need to have high power density<sup>3</sup>; be compatible with processed fuel and air; start up quickly and respond rapidly to frequent load changes; resist shock and vibration; and be relatively easy to control and maintain.

Alkaline fuel cell technology (AFC) is fully developed since the 1960s when the technology became NASA's choice for manned space flight. Alkaline fuel cells are capable of good power density, but they cannot tolerate even very low concentrations of carbon dioxide which is a major constituent of the processed fuel. Carbon dioxide will react chemically with the alkaline electrolyte to irreversibly clog electrolyte and electrodes with the solid carbonate formed in the reaction. In automotive applications, it will be impractical to remove carbon dioxide completely from the processed fuel, eliminating the alkaline fuel cell from consideration.

The phosphoric acid fuel cell (PAFC), currently being commercialized for stationary power applications, can use ambient air and processed fuel but has only modest power density, a deficit that translates into relatively large volume and weight as well as higher cost. Another disadvantage is that the PAFC cannot generate power at ambient temperature but must be preheated to at least 100°C before current can be drawn. Meeting the automotive requirement for rapid start-up would, therefore, be very difficult. Once at operating temperature, PAFCs must always be kept below 0.8 Volt per cell to prevent corrosion of key cell components, making it impractical to keep the fuel cell at open circuit (idle) for extended periods when hot.

On the plus side, PAFCs, because of their operating temperature of around 200°C can accept up to about 1% carbon monoxide in the fuel stream; this reduces fuel processing system complexity. Also, the higher operating temperature improves overall efficiency by permitting a better thermal match between the fuel cell and the fuel processor. Thus, if a transportation application (unlike cars) can tolerate slow start-up and restrictions on load cycling, the system advantages resulting from higher temperature operation could make the PAFC technology an acceptable option. Heavy duty road and/or rail transportation systems might be able to accept these conditions and, also, the somewhat higher cost of PAFC technology.

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<sup>3</sup> Cost and volume of a fuel cell stack with given power rating are inversely proportional to peak power density, i.e., the maximum power that can be delivered per unit volume of cell stacks. Achieving competitiveness with the remarkably low-cost, high-power-density internal combustion engine requires development of automotive fuel cells with the highest possible power densities compatible with good efficiency and adequate service life.

Methanol is the only practical carbonaceous fuel that has significant electrochemical reactivity at fuel cell electrodes in the temperature range of interest for automobile applications. Taking advantage of this reactivity, the “direct” methanol-air fuel cell (DMFC, see Table II-1) can be almost as simple as a hydrogen-air fuel cell while able to use a readily stored, relatively inexpensive fuel. The direct methanol fuel cell has been under laboratory study for a number of years, typically in configurations very similar to PEM hydrogen-air fuel cells: platinum and platinum alloy-catalyzed, porous electrodes for air and for methanol (fed to cells as vapor), with electrodes separated by a proton exchange membrane. However, the DMFC has been handicapped by two major problems: poor performance (current density well below the levels required for automotive applications) and rapid diffusion of methanol through the membrane to the air electrodes where it is readily oxidized in an electrochemical “short circuit” reaction. This methanol “crossover” problem not only reduces fuel utilization efficiency substantially (typically by 30% or more), and methanol depresses the potential of the air cathode and thus the cell voltage, thereby causing an additional loss of energy efficiency. Research during the past five years has improved methanol anode activity significantly and identified possible approaches to reducing the crossover problem. Motivated by these advances and the inherent attractiveness of the DMFC concept, many of the organizations engaged in the development of automotive PEM fuel cell technology have started laboratory work on the problems limiting the prospects of the DMFC. The progress achieved in some of the leading programs is reviewed briefly in Section III.1.F.

The first of the technologies listed in the table above is the proton exchange membrane (PEM) fuel cell. Like all other candidate fuel cell technologies (except the direct methanol cell, see comments above), the PEM technology requires a fuel processor if operated with carbonaceous fuels. Nevertheless, because it operates at relatively low temperature, can use air, and has excellent performance with hydrogen, the PEM fuel cell is coming closest to meeting automotive application requirements. Not surprisingly, all ongoing programs developing automotive fuel cell technology and systems are concentrating their efforts on the PEM technology. The Panel’s investigations, therefore, focused almost exclusively on this technology and the technical and institutional challenges surrounding its development into competitive automotive power sources for mass produced automobiles.<sup>4</sup>

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<sup>4</sup> Many features that make PEM technology the best candidate for vehicle propulsion also make it attractive for stationary power generation. Sizable efforts are now underway worldwide to develop PEMFCs for small-scale electric power generation in the 50 to 250 kW range and for small stand-alone stationary power systems in the 1 to 10 kW range. Successes in the development of automotive fuel cell technology — especially the achievement of the needed low costs — are likely to benefit the stationary applications which have less stringent cost and performance requirements. Conversely, development and introduction of PEM fuel cells into stationary power generation applications could have cost-reducing benefits for the automotive application because of shared investments in manufacturing facilities in the near term and larger production volumes in the longer term.

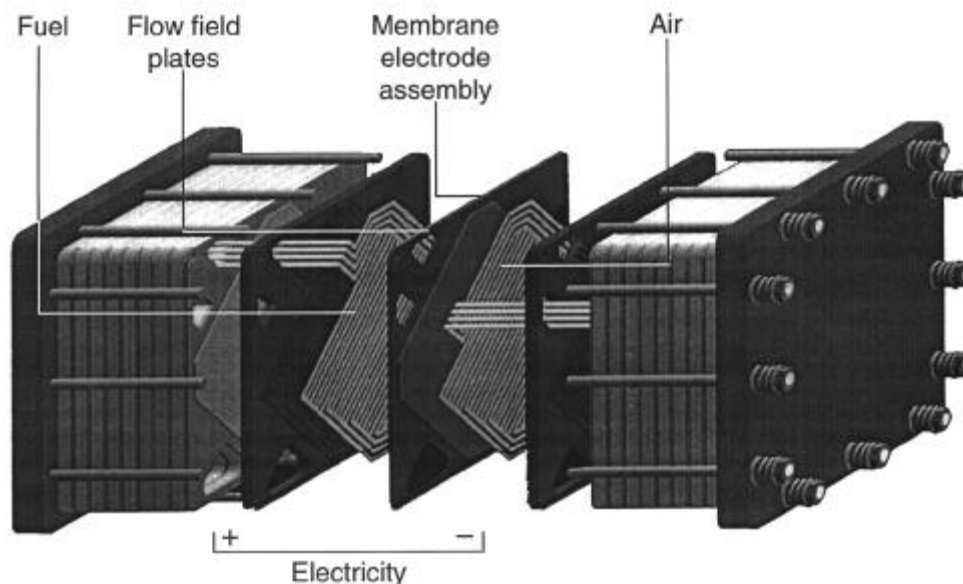
## B. PEM FUEL CELL STACKS

Figure II-1 is a schematic representation of a single PEM fuel cell. At representative values of current density (e.g., 1 amp/cm<sup>2</sup>), cell voltage (about 0.7 volts) and cell area (e.g., 500 cm<sup>2</sup>), a single cell can deliver  $1 \times 0.7 \times 500 = 350$  watts. To give a full-size fuel cell electric vehicle adequate acceleration and top speed, about 50-65 kW, or 150-200 cells @ 350 watts are needed. (A larger number of cells is required to attain the same power level with cells of smaller area.) To build up practical levels of voltage and avoid the need to make electric connections to each individual cell, cells are assembled end-to-end in good electric contact with each other, as shown in Figure II-2.

For automotive applications, such cell stacks need to be very compact, with a volume of no more than about 50 liters, or about 250-350 cm<sup>3</sup> per cell. For a cell of 500 cm<sup>2</sup> area, this requirement translates into a cell thickness of 0.5-0.7 cm. This small dimension must accommodate membrane, anode and cathode, allow uniform gas distribution to both surfaces of each electrode as shown in Figure II-3, and leave space for gas-impervious conductors between adjacent cells.

One key to meeting these stringent requirements is the development of the “membrane-electrode assembly” or MEA. An MEA is an anode-PEM electrolyte-cathode composite structure (shown in the center of Figure II-3) in which each layer is made as thin as possible without losing the mechanical integrity of the composite structure or the electrochemical activity of the two electrodes. Anode and cathode consist of a conducting catalyst support material (most often a porous form of carbon) which is mixed or impregnated with a platinum or platinum alloy catalyst and applied to opposite sides of the membrane. The functional advantages of such a structure include short diffusion paths of air and fuel gas to the electrochemical reaction sites, intimate contact of electrodes with the polymer electrolyte, and low ionic resistance of the membrane — the properties needed to sustain high current and power densities.





**Figure II-3. PEM Fuel Cell Stack**

The other key development for achieving high power densities is the separator plate. As shown in Figure II-3, separator plates contain channels on both sides of a gas-impervious layer which distribute hydrogen-containing fuel gas and air to the anode and cathode sides of the membrane, respectively. Separator plates must be conducting and in electric contact with the electrodes to collect the current and transmit it between adjacent cells, and they must be impervious to contain the reactant gases within each half cell. The gas inlets and outlets of the separator plates must be connected separately to air and fuel gas inlet and outlet manifolds, respectively; manifolds can be arranged within the stacks or external to them.

The capabilities to remove water and heat (the products of the cell reaction), and tolerate inert gases (nitrogen from air, carbon dioxide from the input fuel gas, see fuel processor section below) must be designed into the cell and stack structures. In the Ballard stack design (Figure II-3), air in excess of the amount required to sustain the oxygen reduction cathode reaction is flushed over the cathode surface to remove product water as vapor. Heat is removed by a liquid coolant stream flowing through cooling plates inserted in the stack at regular intervals.

The cell stack assembly is held together with tie rods that apply a compressive force on the stacked cells by means of end plates. These plates also provide connections for air and fuel gas flow to and from the stack, coolant circulation, and the electric power output of the stack. The output voltage is the sum of the individual cells electrically in series within the stack, typically in the order of 150 to 300 volts for an automotive PEM stack.

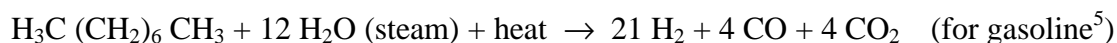
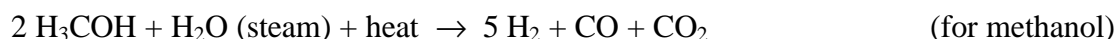
## C. FUEL PROCESSORS

As noted in Section II.A, gasoline and other carbonaceous fuels do not have adequate electrochemical reactivity to be used directly in PEM or other fuel cells. A catalytic-chemical fuel processor is required to convert these fuels to hydrogen-rich fuel gases that provide hydrogen fuel for operation of the PEM fuel cell stack described above. Because the stack's hydrogen demand varies with the electric load placed on it by the FCEV's power demand, fuel processors for automotive fuel cell engines must be able to start up quickly, follow demand rapidly, and operate efficiently over a wide range of conversion rates. Also, fuel conversion needs to be essentially complete over the entire load range, the carbon monoxide level in the processed fuel entering the stack must be very low to avoid poisoning the anode electrocatalysts, and emissions of pollutants need to be zero or extremely low if fuel cell electric engines are to deliver on their environmental promise.

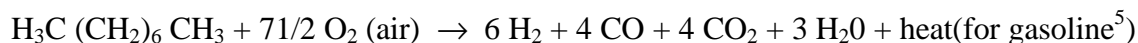
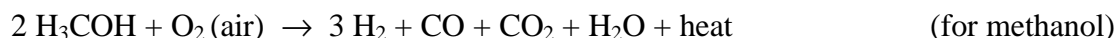
Automotive fuel processors need to provide not only all these capabilities, but they must be very compact and low in cost. None of the various fuel processing reactors currently or previously used in the petrochemical, chemical and related industries are designed for, or are capable of, meeting this combination of requirements. Not surprisingly, design, engineering and low-cost manufacturing of fuel processors are among the most difficult challenges to developing practical, cost-competitive fuel cell electric engines.

The chemical principles and practical requirements governing automotive fuel processor design and performance are discussed here, beginning with two alternative reactions used in the primary steps to convert methanol or gasoline:

(a) steam reforming



(b) partial oxidation



(c) "autothermal reforming", that is, combinations of reactions (a) and (b) in proportions such that the heat released in the partial oxidation approximately balances and provides the heat required for steam reforming of methanol or gasoline, respectively.

Table II-2 compares the amounts of hydrogen theoretically available from steam reforming or partially oxidizing one gallon each of several practically important fuels. The differences in hydrogen content are due

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<sup>5</sup> The equation uses the chemical formula for octane, a hydrocarbon representative of gasoline which is a mixture of hydrocarbons with elemental compositions similar to that of octane.

to differences in the hydrogen percentage of the fuel's elemental composition, its energy content, and its density. Other important characteristics of candidate fuels for fuel cells are summarized in Table II-3.

**Table II-2. Hydrogen Content of Common Fuels**

**HYDROGEN CONTENT VIA FUEL PROCESSING<sup>a</sup>**

**APPROXIMATE EQUIVALENCY, kg H<sub>2</sub>/kg FUEL**

<b>Fuel</b>	<b>Steam Reforming</b>	<b>Partial Oxidation</b>
Methanol (CH <sub>3</sub> OH)	0.189 (0.568 kg/gal)	0.126 (0.377 kg/gal)
Ethanol (C <sub>2</sub> H <sub>5</sub> OH)	0.263 (0.791 kg/gal)	0.219 (0.636 kg/gal)
LNG (CH <sub>4</sub> )	0.503 (0.777 kg/gal)	0.377 (0.573 kg/gal)
LPG (C <sub>3</sub> H <sub>8</sub> /C <sub>4</sub> H <sub>10</sub> )	0.456 (0.873 kg/gal)	0.316 (0.609 kg/gal)
Gasoline (C <sub>8</sub> H <sub>15.4</sub> )	0.430 (1.14 kg/gal)	0.284 (0.755 kg/gal)
Diesel Fuel (C <sub>14</sub> H <sub>25.5</sub> )	0.424 (1.35 kg/gal)	0.279 (0.873 kg/gal)

<sup>a</sup> Includes CO conversion via water gas shift reaction

**Table II-3. Candidate Fuels for Fuel Cells**

<b>Fuel</b>	<b>Formula</b>	<b>Low Heat Value Btu/lb (kcal/kg)</b>	<b>Specific Weight lb/ft<sup>3</sup> (kg/l)</b>	<b>Specific Energy Btu/gal (kcal/l)</b>	<b>Heat of Vaporization Btu/lb (kcal/kg)</b>	<b>Vapor Pressure lb/in<sup>2</sup> (mm Hg)</b>	<b>Boiling Point °F (°C)</b>	<b>Approx. Flammability Range % by vol.</b>
Ethanol	C <sub>2</sub> H <sub>5</sub> OH	11,596 (6,442)	49.08 (0.789)	76,422 (5,089)	376 (210)	~1.5 (~75)	172 (78.3)	4-14
Gasoline <sup>a</sup>	C <sub>8</sub> H <sub>18</sub>	~19,000 (10,556)	44.78 (0.720)	114,130 (7,600)	128 (71)	~9.7 (~500)	258 (125.7)	1-6
Hydrogen (5,000 lb/in <sup>2</sup> )	H <sub>2</sub>	51,530 (28,628)	1.43 (0.023)	9,881 (658)	—	—	-423 (-252)	4-74
Natural gas <sup>b</sup> (Methane)	CH <sub>4</sub>	21,485 (11,936)	14.31 (0.230)	41,222 (2,745)	—	—	-260 (-162)	5-13.5

(5,000 lb/in <sup>2</sup> )								
Methanol	CH <sub>3</sub> OH	8,636 (4,798)	49.26 (0.792)	57,065 (3,800)	473 (263)	~2.4 (~125)	148 (64.5)	3-36

<sup>a</sup> Gasoline is a blend of hydrocarbons and varies with producer, application and season. N-Octane is reasonably representative of properties except vapor pressure, which is intentionally raised through the addition of lighter specie. The vapor pressure value shown is typical of gasoline, not N-Octane.

<sup>b</sup> Natural gas is a mixture of gases which varies considerably depending on the source. However, methane is the primary constituent of all natural gas and its properties are reasonably representative.

Steam reforming is the fuel conversion process of choice if waste heat of sufficiently high temperature is available from the fuel cell stack — for example, from high-temperature or intermediate-temperature fuel cells including the phosphoric acid technology. If steam reforming is selected for PEM technology-based fuel cell electric engines, the heat needed to drive the fuel reforming reaction must be provided by burning some fuel and/or the residual hydrogen in the stack tail gas. One challenge in that approach is to achieve rapid cold start-up because heat must be supplied to the reformer from the outside. Nevertheless, properly designed and thermally integrated with sources of waste heat, steam reforming is an attractive choice because of its high efficiency.

Partial oxidation can be carried out in catalytic or thermal (combustion) reactors. Reactor design can be relatively simple, and air-fuel ratios are readily controlled to avoid undesirable deposition of solid carbon in the reactors. However, partial oxidation is exothermic, and the heat released comes at the expense of hydrogen formation and reformer efficiency. Also, nitrogen from air dilutes hydrogen further which makes it more difficult to achieve the desired high degree of hydrogen utilization in the fuel cell stack. Partial oxidation by itself would, therefore, not provide the efficiency needed for automotive fuel processors.

Some of the heat released in partial oxidation can be used to generate steam which is then added to the fuel input, to move the reactor toward the autothermal chemical composition and heat balance conditions of reaction (c) above. The intimate combination of exothermic and endothermic processes increases reactor thermal efficiency and reduces or eliminates some of the heat transfer that would be needed otherwise to avoid excessive heat and efficiency losses. Air-fuel and steam-fuel ratios can be controlled readily and rapidly over a wide range which gives good control over the reactor chemistry and hydrogen output. The result is a relatively simple and efficient primary processing unit.

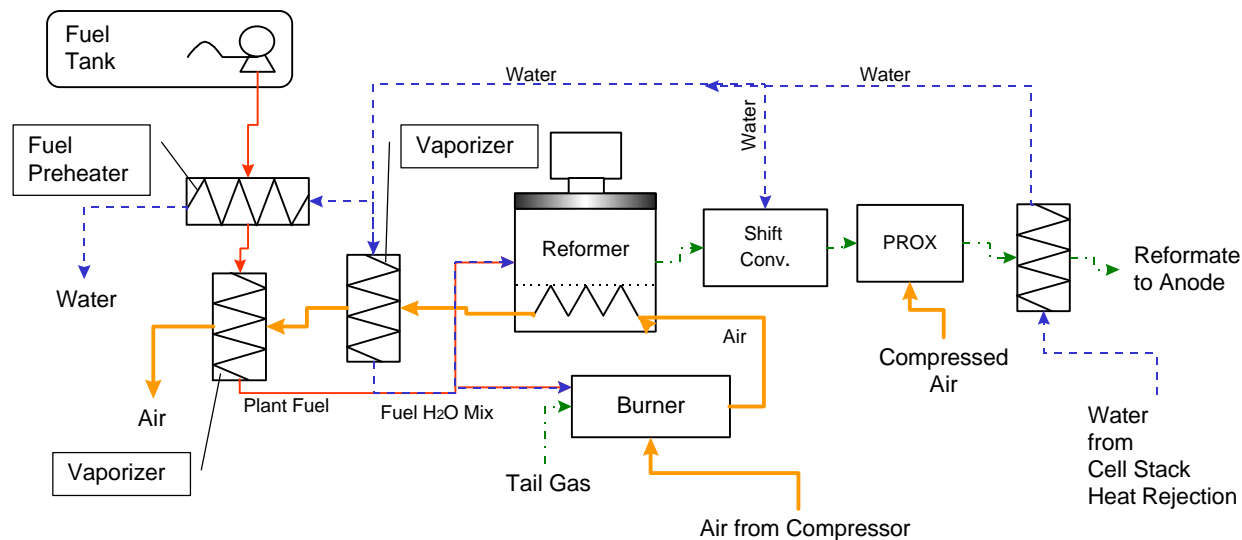
All primary fuel processing reactions produce substantial amounts of carbon monoxide (CO), see (a) and (b) above. CO, unfortunately, is incompatible with PEM fuel cell stacks: some of it becomes strongly

adsorbed and deactivates (“poisons”) the platinum metal or alloy electrodes, and the rest passes unchanged through the stack, with the attendant loss of heating value. To recover the heating value of CO in the form of hydrogen, the primary processor output stream is processed with additional steam in a secondary unit, the water gas shift reactor, according to  $\text{CO} + \text{H}_2\text{O (steam)} \rightarrow \text{H}_2 + \text{CO}_2$ . This reaction reduces the CO content of the hydrogen-rich gas stream to about 1% (10,000 ppm), still far above the approximately 10 ppm tolerance limit of a typical anode catalyst.

To achieve the required 1000-fold reduction in CO content, the gas stream is treated in a third process unit. This unit can be a preferential oxidation (“PROX”) reactor in which CO is oxidized with added air in preference to the hydrogen present in much higher concentration according to:  $\text{CO} + 1/2 \text{O}_2 \rightarrow \text{CO}_2$ . Alternatively, CO can be reduced by passing the processed fuel stream through a “methanation” reactor according to:  $\text{CO} + 3 \text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}$ . Because some hydrogen is lost in both alternatives, it is very important to achieve the lowest practical concentration of CO in the water gas shift reaction and the highest possible CO tolerance of the fuel cell stack.

The complexity of a multi-unit fuel processor is suggested by the process flow diagram in Figure II-4 which includes other functions needed for fuel processor operation such as fuel vaporization, air supply, catalytic burning of anode tail gas, and various heat exchangers.

Not included in Figure II-4 but also important are the components and systems required to control the flow of process gases. All these processor components and functional subsystems need to be accommodated in the very limited space and provided at the low costs that can be allocated for automotive fuel processors.



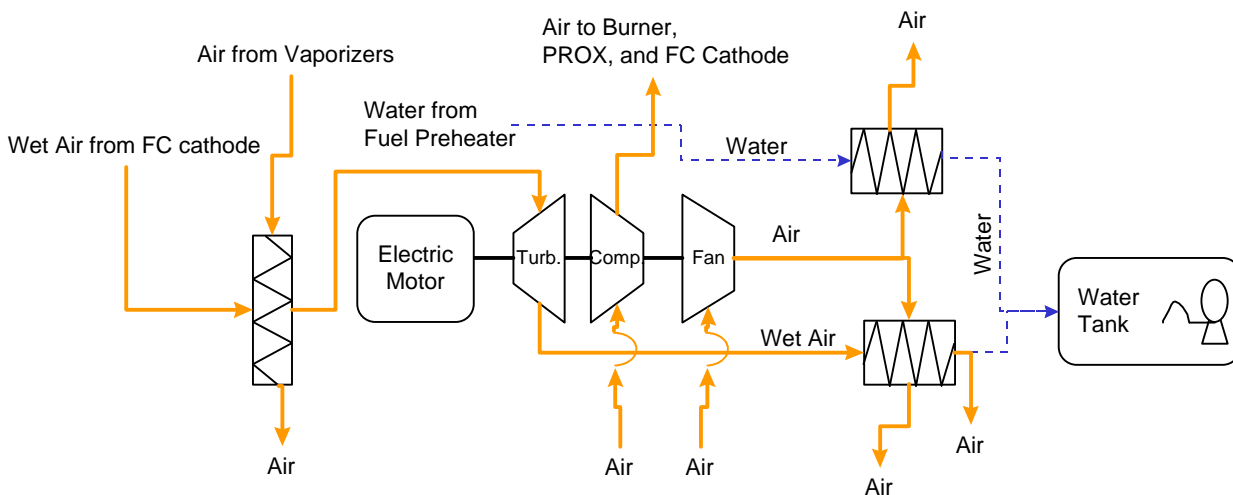
**Figure II-4. Fuel Processor Flow Diagram**

#### **D. BALANCE OF PLANT**

For the purposes of this report, Balance of Plant (BoP) comprises all PEM fuel cell electric engine (power plant) components beyond the fuel cell stack, the fuel processor, and the power conditioner.

The air management system is the most important BoP component of a fuel cell power plant.

As shown schematically in Figure II-5, the air management/handling equipment for pressurized systems consists primarily of a compressor and expander and the electric drive motor for the compressor. Operation at elevated pressure (e.g., 2-3 atmospheres) is favored by most developers of fuel cell systems. For larger fuel cell systems operated at or near full power, the additional capital cost and energy required for pressurization tends to be more than offset by the cost reduction and/or efficiency gain made possible by the higher specific performance (current and power density) of pressurized stacks. At near-atmospheric pressure operation, only a blower and its drive motor is required. The heat exchangers of the air handling system serve to condense and recover product water for reuse in the fuel processor.



**Figure II-5. Air Management System Flow Diagram**

Water and thermal management also are key balance-of-plant functions. In a fuel cell power plant, the temperatures of a number of critical components (particularly the stack and the different reactors of the fuel processor) have to be carefully controlled, and the flow and utilization of heat from several sources within the system has to be managed efficiently to achieve high overall efficiency. A number of high-performance heat exchangers are required to meet these objectives. The details of thermal management are dictated by the specific subsystem and system designs.

Water plays a very important role in the operations of PEM fuel cell stacks and fuel processors. The pure water produced in cells from the electrochemical combination of hydrogen and oxygen must be removed continuously from the stack. This is accomplished either by condensing water in the cathode exhaust gas (in acid electrolytes like PEMs, water is formed at the cathode), or by using a combination of capillary action and pressure to “wick” water from the stack to a reservoir. Both approaches are now in use. At the same time, the gases entering the stack must be humidified to prevent PE membranes from drying out which could result in crossover of hydrogen and/or oxygen and irreversible stack damage due to the heat generated by this “chemical short circuit.” Pure water also is used as coolant to transfer waste heat from the stack to the fuel processing system and/or to a radiator. Stack protection against freezing of cooling water is one of the many requirements that must be met by fuel cell system design and operation.

Water is both consumed and produced in the various fuel processing reactions, with the quantities and flows dependent on the specific chemical approaches employed (see preceding section). Water is a key reactant in the steam or autothermal reforming and water gas shift reactions, typically added to reactor input

streams in the form of steam that is generated with heat available, for example, from the fuel processor exhaust; water is produced in partial oxidation. Excess water must be removed from the hydrogen-rich anode input gas before it enters the stack. It can be recycled for fuel processing although some purification may be required.

It is evident that the need for well-controlled management of heat and water places a significant number of constraints and component requirements on PEM fuel cell power plants. While meeting these requirements does not present fundamental problems, doing so with high reliability and at potentially very low costs is a significant challenge.

Controls are critically important ingredients of each major fuel cell power plant subsystem and the integrated system. Parameters needing to be controlled include various mass flows, many temperatures and pressures, turbine shaft speed and bypass, and a number of electrical parameters. These control functions need to be provided not only over a wide range of system power levels, but for substantially different system conditions that include cold start, rapid load transients, and system shutdown. The fuel cell engine control subsystem needs to include a substantial number of sensors, valves for air and pumps for fuel flow, microprocessors for the numerous control functions, a computer-based master control, and the mechanical and electric hardware required for connecting all these components with the appropriate subsystems. Not surprisingly, controls contribute significantly to fuel cell power plant cost.

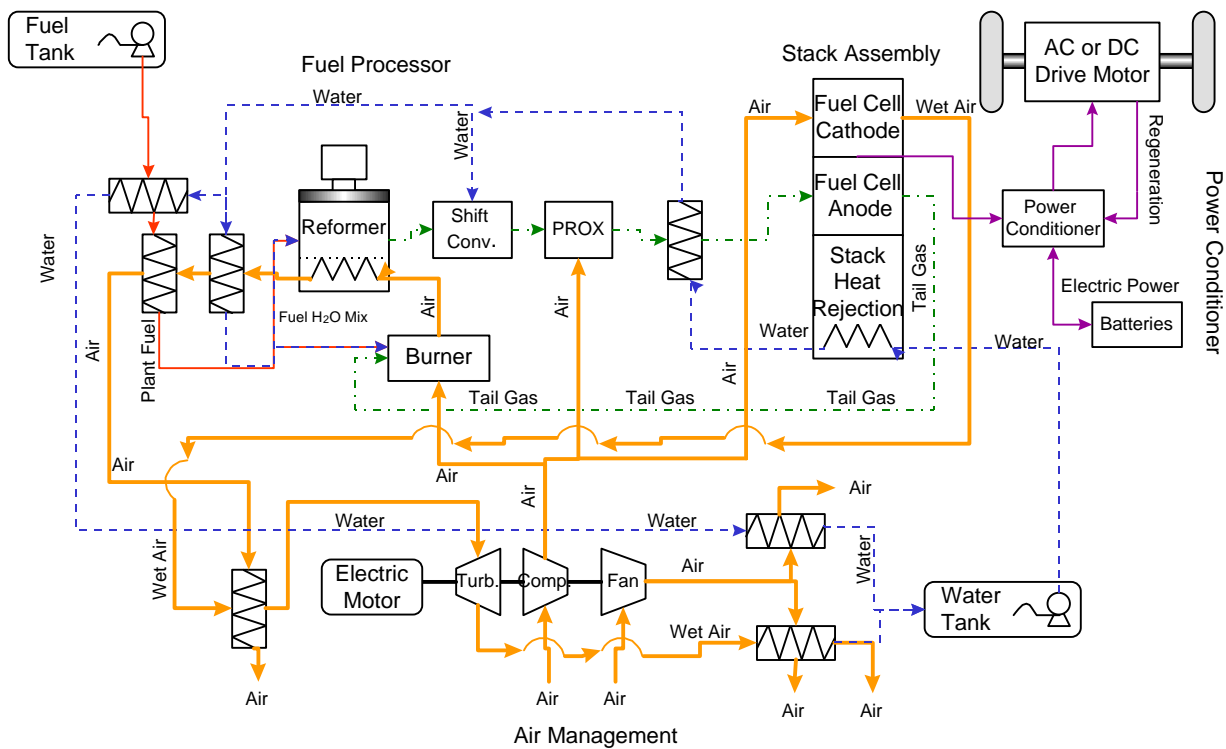
## **E. INTEGRATED FUEL CELL POWER PLANT (ELECTRIC ENGINE<sup>6</sup>)**

Figure II-6 shows schematically how the flows of air, processed-fuel, heat and water are integrated in a complete fuel cell electric engine consisting of a fuel processor, a fuel cell stack, and air management and other balance-of-plant components distributed throughout the power plant.

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<sup>6</sup> In this report, the term “fuel cell electric engine” denotes the complete fuel cell power plant including the power conditioner that converts and controls the direct current output of the fuel cell and serves as the interface to the electric drive motor.





**Figure II-6. Fuel Cell Electric Engine (Flow Diagram)**

One important aspect of energy integration within the power plant concerns utilization of the hydrogen. A certain amount of unreacted hydrogen must be allowed to pass through the anode compartments of the stack as part of the “tail gas” (mostly carbon dioxide) since portions of the stack would “starve” electrochemically if all the hydrogen were used up within cells. Loss of unreacted hydrogen would constitute an unacceptably large loss of energy and system efficiency. As illustrated in Figure II-6 for a typical system configuration, the tail gas is, therefore, passed through a catalytic device in which residual hydrogen is burned at relatively low temperature (in part to avoid formation of  $\text{NO}_x$ ), and the resulting heat is transferred by means of the burner exhaust gas to the steam reformer. There the hot gas provides some of the heat needed to drive the primary reforming reaction in which the fuel-steam mixture is converted to hydrogen-rich gas (see also Section II.1.B, above).

For another example of necessary thermal integration, refer again to Figure II-6. The hydrogen-rich fuel gas (“reformat”) leaving the reformer contains appreciable heat energy. To avoid a significant loss of system efficiency, the excess heat in this gas is first exchanged with the fuel and water vaporizers and subsequently with the cathode input air. After exiting the stack, the residual air still has sufficient thermal

energy (from this heat exchange, plus the heat from the losses associated with the reactions in the fuel cell stack) to help the expander drive the compressor, saving additional energy in the process.

In practical fuel cell power plants, substantial mass and extensive heat flows between the major subsystems must be accommodated as efficiently as possible while insuring that the system is operable and reliable over the wide range of conditions imposed by the time-variable power demand of the vehicle. Rapid cold start-up and load changes represent particularly difficult requirements for system operation. Over the entire range of system and subsystem power levels and chemical conditions, emissions of pollutants must be avoided. In addition to mass flow and thermal integration, compact physical integration must also be accomplished because fuel cell power plants will need to fit into the very limited spaces typically available for automobile engines. Finally, all these requirements must be met with fundamentally inexpensive materials and with components and subsystems designed for low-cost mass manufacturing. Even without considering the technical details of all integration requirements, technical approaches and functional components, it is clear that the objectives of system integration translate into numerous and complex challenges for the developers and prospective manufacturers of automotive fuel cell engines.

## **II.3 SYSTEM EFFICIENCY AND EMISSIONS CONSIDERATIONS**

### **A. FUEL CELL SYSTEM EFFICIENCY**

Much of the interest in fuel cells is motivated by their fundamental promise of significantly higher energy conversion efficiencies than combustion-based engines. In practice, many process steps are required to convert the energy of the input fuel into the electric energy output of the fuel cell stack, and inefficiencies are associated with each of these steps. As illustrated in Figure II-6 and briefly discussed in the preceding section, careful energy integration is essential if the basic potential of fuel cell electric engines for superior efficiency is to be realized in practice.

We define fuel cell system efficiency here as the electric power output from the system's power conditioner divided by the lower heating value of the rate at which fuel is consumed by the system. Defined this way, efficiency is an instantaneous value that will change with conditions (load; status of process units; ambient conditions) under which the fuel cell engine is operated. Generally, efficiency will be highest at steady-state in the primary design range, lower near the design limits (e.g., maximum or very low power), and lowest at start up when energy is needed to heat the fuel processor and stacks.<sup>7</sup>

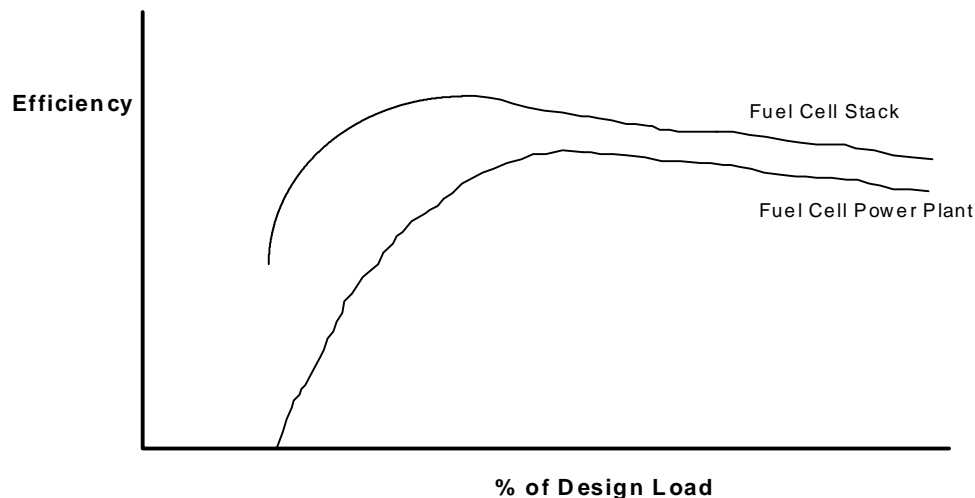
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<sup>7</sup> For meaningful comparisons of efficiencies among different fuel cell engines or with combustion engines, conditions need to be specified in some detail. Measuring efficiencies for well defined, readily executed driving cycles is the best approach to establishing realistic values

Within the fuel cell power plant, the stack represents the single largest loss of usable energy and, thus, of efficiency. Stack efficiencies (stack DC electric output divided by fuel energy input) typically are 50 to 60% at design power. The losses arise from ohmic losses in cells and the energy expended to overcome the resistance to electrochemical changes at the electrodes; they appear as heat that must be removed from cells and the stack. High catalyst activities, highly conducting membranes and careful electric design of MEAs, cells and stacks are essential to minimize stack efficiency losses.

Fuel processors also contribute to fuel cell system efficiency losses for fundamental reasons (use of chemical energy to provide the thermodynamic driving force for irreversible processing reactions) and in practice because not all heat lost from the process units can be recovered. However, on a heating value basis thermally well-integrated fuel processors (see Section II.2.E, above) can deliver up to about 85% of the fuel input as hydrogen output.

While stack losses decrease as load is reduced, the inevitable losses in BoP components (especially the components of pressurized air handling systems) do not decrease linearly with load. As a result, fuel cell system efficiency usually declines with load as shown in Figure II-7, although not as precipitously as some combustion engines.



**Figure II-7. Fuel Cell Stack and Power Plant Efficiency as Function of Load**

Pressurization can have a significant effect on fuel cell efficiency. Pressurization will increase stack efficiency by raising voltage at a given current density. On the other hand, even under the most favorable conditions a considerable fraction of stack power (up to 25% at design power, more at low loads) is needed to compress air to the relatively modest pressures (typically, 2-3 atmospheres) used in many fuel cell systems. To

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of “average” efficiency, but for fuel cell engines this measurement must await availability of representative, driveable fuel cell electric

recover some compression energy, turbine expanders can be used. Unfortunately, with simple, potentially inexpensive compressor-turbine systems it is difficult to achieve good efficiencies at the relatively low flow rates needed for fuel cell systems in the 50 kW range or below. Quantification and optimization of the trade-offs between efficiency, power density and cost as a function of pressure is a complex but important task for fuel cell engine designers and developers considering pressurized operation.

## **B. EMISSIONS FROM FUEL CELL ENGINES**

The potential for pollution-free power generation has been a major driver in the development of fuel cells over the past 30 years, and the expectation of zero or near-zero emissions also is responsible for much of the current interest and investment in the development of fuel cell electric engines for automobiles.

Hydrogen-air (oxygen) systems are the only fuel cells that have zero emissions from the vehicle<sup>8</sup>: water is the only product, and no combustion process is involved in fuel cell operation. Theoretically, the processing of gasoline, methanol and other carbonaceous fuels into hydrogen-rich gases suitable for use in fuel cells also could be done without formation of pollutants, with water and CO<sub>2</sub> as the only reaction products. In practice, fuel processor and fuel cell system operation involve auxiliary combustion processes, and thus the potential exists for formation of NO<sub>x</sub> and products of incomplete combustion including CO and/or carbonaceous gases or vapors. However, under the chemical conditions and constraints prevailing in properly operating methanol and gasoline powered fuel cells, these emissions should be close to zero for NO<sub>x</sub> and extremely low for carbonaceous pollutants including CO. The main reason is that the auxiliary combustion processes involve relatively small amounts of fuel and, like the burning of unconverted hydrogen, are carried out at rather low temperature (NO<sub>x</sub> ≈ 0) and under close control in catalytic burners.

The few available emissions data for bus (phosphoric acid) fuel cell power plants do indicate near-zero NO<sub>x</sub> and very low other emissions, despite the fact that these power plants were largely experimental and not optimized. Confirmation of near-zero emissions performance under representative operating conditions (including cold start and rapid load changes) will be an important aspect of the PEM fuel cell electric engine and vehicle test programs of the major developers over the next several years.

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vehicles.

<sup>8</sup> "Upstream" pollutant emissions occur if hydrogen is produced from natural gas or other carbonaceous feedstocks including coal, but such emissions normally are small and remote from population centers. Such processes, of course, release the greenhouse gas CO<sub>2</sub> to the atmosphere. However, because of the high efficiency of hydrogen-air fuel cells the total transportation energy system emissions of CO<sub>2</sub> would be significantly lower than those of the current system of internal combustion engines using petroleum-derived fuels. FCEVs using gasoline or methanol also would have lower total CO<sub>2</sub> emissions because of the expected higher average efficiency of automotive fuel cells compared to ICE engines.

## **II.4 VEHICLE INTEGRATION CONSIDERATIONS**

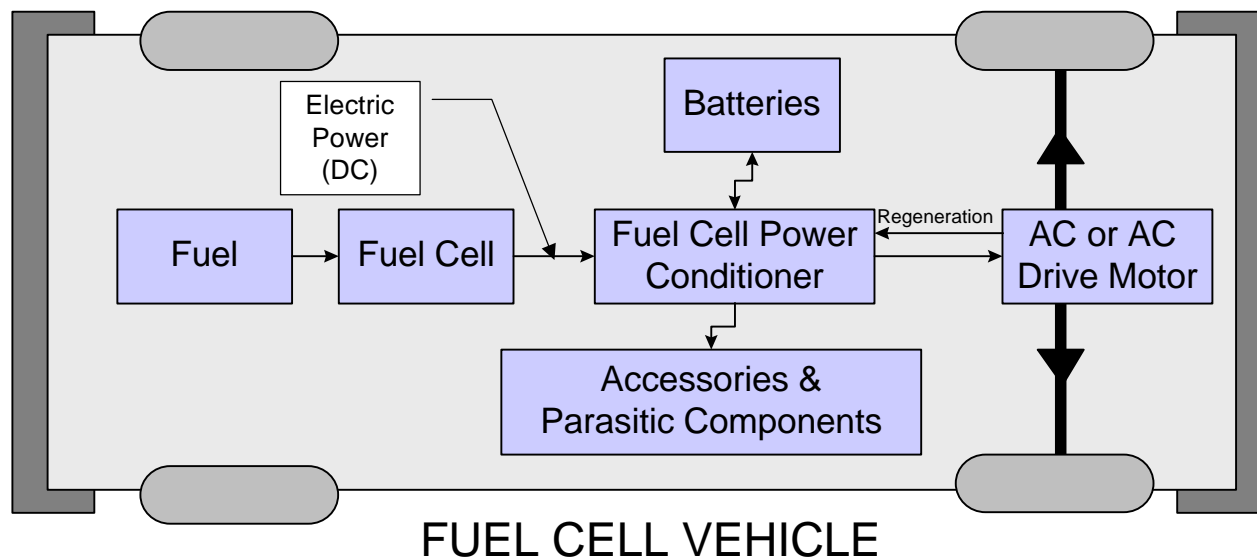
### **A. FUELS FOR AUTOMOTIVE FUEL CELL ENGINES**

When integrating a PEM fuel cell power plant (engine) with a vehicle, consideration needs to be given to the on-board fuel supply subsystem. For gasoline and related liquid hydrocarbon fuels, no special provisions beyond current fuel storage practice appear necessary. Some of the tank volume saved due to the higher efficiency of fuel cells compared with IC engines will be available for the required storage of product water. Technology for the transfer and storage of methanol, the other candidate liquid fuel for PEM fuel cells, also can be considered available as a result of the substantial experience with methanol-powered ICE cars in California and the Georgetown/DOE/DOT methanol fuel cell buses. The considerations surrounding availability of methanol on the scale that would be required by a large population of fuel cell electric vehicles are discussed in Section III.2.B, below.

The difficulty to store a sufficient quantity of hydrogen onboard automobiles is one of the reasons (the other being the high cost of the required hydrogen production and distribution infrastructures, see Section III.2.A) why hydrogen is not now being considered as a primary fuel for fuel cell-powered automobiles. Research on advanced concepts for high-density storage of hydrogen bound to other elements (metals/alloys; possibly, forms of carbon) is underway but as yet has not resulted in the breakthroughs needed to solve the on-board hydrogen storage problem.

### **B. POWERTRAIN**

A fuel cell electric engine supplies electric energy to the electric drive train through its power conditioning subsystem, as shown schematically in Figure II-8.



**Figure II-8. Functional Subsystems of Fuel Cell-Battery Hybrid Electric Vehicle**

The scope of this assessment excludes the power conditioner and the electric drive train, for the reason already mentioned: the power electronic and electric motor technologies required for fuel cell electric vehicle propulsion are essentially the same as those used in current battery-powered electric vehicles. These technologies have reached a high state of development and are commercially available although at relatively high costs. Manufacturing on the scale needed to make fuel cell stacks, processors and other balance-of-plant components cost-competitive is expected to also reduce the cost of power conditioners and electric drivetrain technology to acceptable levels.

Figure II-8 includes batteries as a component of the electric drive system, making the system shown in the figure a fuel cell-battery “hybrid” electric vehicle. Because the availability of an energy storage unit onboard a fuel cell electric vehicle can substantially affect the requirements that must be met by the fuel cell (i.e., the combination of fuel cell stack, fuel processor and the balance-of-plant components needed to operate the fuel cell), the characteristic advantages and disadvantages of hybrid systems are discussed in more detail in the next section.

### **C. HYBRIDIZATION**

The addition of an energy storage capability (typically, a battery) to an engine serving as the primary power source for a vehicle is generally referred to as “hybridization.” The main advantages expected from

hybridization include (1) recovery, storage and re-use of the vehicle kinetic energy normally dissipated as heat during braking, with a consequent increase in vehicle fuel efficiency, (2) use of the energy storage device to respond rapidly to load changes (including cold start), thereby permitting the primary power source to be operated more efficiently and cleanly at constant or slowly varying power, and (3) using the storage unit to provide power assist for acceleration and hill climbing, thus permitting a smaller, potentially less expensive and more efficient primary engine to be used. One other feature and advantage of hybrid drive systems that have a substantial energy storage capacity onboard the vehicle is the possibility to utilize electricity provided by the electric grid as a second, clean and inexpensive source of energy for zero-emission urban/suburban travel.

For vehicles with methanol or gasoline-powered fuel cell engines, the most important advantage of hybridization will be the instantaneous availability of vehicle motive power from the storage device. Using the storage device to provide some or all of the vehicle power during cold start eliminates the need for near-instant start-up of the fuel processor, possibly the technically most difficult requirement for a fuel cell electric engine. Also, with the storage device responding instantly to load transients, fuel processor and stack can remain in their most efficient operating range during changes in power demand. The rapid load response of batteries or other fast-responding electric storage devices promises correspondingly good vehicle driveability.

On the other hand, hybridization will increase complexity and likely also cost, already a major issue for fuel cell electric engines and vehicles. Inasmuch as fuel cell engines and vehicles will have a power conditioner and an electric drive train, only the cost of the storage device (e.g., the battery itself) is additional. Hybrid systems with a sufficiently large battery energy storage and power delivery capacity will permit a smaller and therefore less expensive fuel cell electric engine to be employed which could offset battery costs entirely or in part. Hybridization presents a number of technical options, impacts on fuel cell engine subsystem requirements, and complex trade-offs between vehicle performance, efficiency, driveability and cost. Moreover, hybridization trade-offs and benefits will be different for the different primary fuels: modest for hydrogen, likely significant for methanol, and yet larger for gasoline which is the fuel relatively most difficult to process.

Because fuel processor and hybrid technologies are still advancing, neither the benefits nor the costs of hybridization can be predicted with any confidence. Not surprisingly, therefore, different fuel cell engine and vehicle developers are following different technical strategies with respect to hybridization. It is important to recognize that the decision for or against hybridization substantially affects most aspects of fuel cell electric engine and drive train development and very likely the characteristics of the resulting product as well.

In summary, the discussions of Section II make clear that diverse and difficult challenges and decisions accompany the development of fuel cells into automotive power plants capable of competing with internal combustion engines. As is discussed in some detail in Section III, these challenges are now being addressed in major and diverse development efforts worldwide. In the United States, fuel cell developers, automobile manufacturers, prospective suppliers of fuel cell component technologies, National Laboratories and university researchers are participating vigorously in these efforts through a wide range of federally and privately funded programs to advance all aspects of PEM automotive fuel cells. To help guide these efforts, U.S. automobile manufacturers, collaborating with DOE and other federal agencies in fuel cell electric engine development under the aegis of PNGV, established quantitative performance, operating and cost goals for automotive fuel cells. The most important of these goals are summarized in Table II-4.

**Table II-4. PNGV Goals for PEM Automotive Fuel Cell Technology**

Stack		Fuel Processor		Power Plant	
Power Density (kW/liter)	Specific Power (kW/kg)	Power Density (kW/liter)	Specific Power (kW/kg)	Cold Start (minutes)	Specific Cost (\$/kW)
Year 2000 0.35	0.35	0.60	0.60	1	150
Year 2004 0.50	0.50	0.75	0.75	0.5	50

The numbers in Table II-4 should not be taken as firm criteria but as aggregate goals for development and as yardsticks for progress, with the understanding that many other factors will co-determine competitiveness and customer acceptance of fuel cell electric engines and vehicles.



